AC Loss Analysis on the Superconducting Coupling Magnet in MICE

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A pair of coupling solenoids is used in MICE experiment to generate magnetic field which keeps the muons within the iris of thin RF cavity windows. The coupling solenoids have a 1.5-meter inner diameter and will produce 7.4 T peak magnetic field. Three types of AC losses in coupling solenoid are discussed. The affect of AC losses on the temperature distribution within the cold mass during charging and rapid discharging process is analyzed also. The analysis result will be further confirmed by the experiment of the prototype solenoid for coupling solenoid, which will be designed, fabricated and tested at ICST.

INTRODUCTION

The muon ionization cooling experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting solenoids and absorbers that may be useful for a neutrino factory [1]. The MICE cooling channel contains two spectrometer modules, three absorber focus coil (AFC) modules that focus and ionization cool the muons in an absorber inside the focusing magnet, and two RF coupling coil (RFCC) modules that reaccelerate the muons back to their original momentum.

The RFCC module comprises a superconducting coupling solenoid magnet mounted around four conventional conducting 201.25 MHz closed RF cavities bounding by thin beryllium windows [2]. Ionization cooling occurs when there is a net loss of transverse muon momentum when the muons pass through the absorber material in the AFC module. The longitudinal momentum of muon beam is then recovered by accelerating the beam with the adjacent four cell 201.25 MHz RF cavity that is in a 2.2 T magnetic field generated by the coupling magnet. A function of the coupling magnet is to produce a low muon beam beta to keep the beam within the iris of thin RF cavity windows.

The engineering design of the MICE coupling magnet had been carried out by the Institute of Cryogenics and Superconductivity Technology (ICST) in the Harbin Institute of Technology (HIT) in collaboration with the Lawrence Berkeley National Laboratory since December, 2006. ICST has been fabricating the two coupling magnets for MICE since March this year.

MICE SUPERCONDCUTING COUPLING SOLENOID

The superconductor used in MCE coupling magnet is standard MRI magnet conductor with a copper to superconductor ratio of four. The nominal RRR for the copper is 70. The superconductor in the coupling coil conductor is 47 wt percent titanium and niobium. The coupling coil conductor has bare dimensions t = 0.95 mm by w = 1.6 mm with R_C = 0.2 mm. which is shown in Figure 1. The conductor has 222 filaments that are nominally 41 μm in diameter. The nominal twist pitch for the conductor is 19 mm.

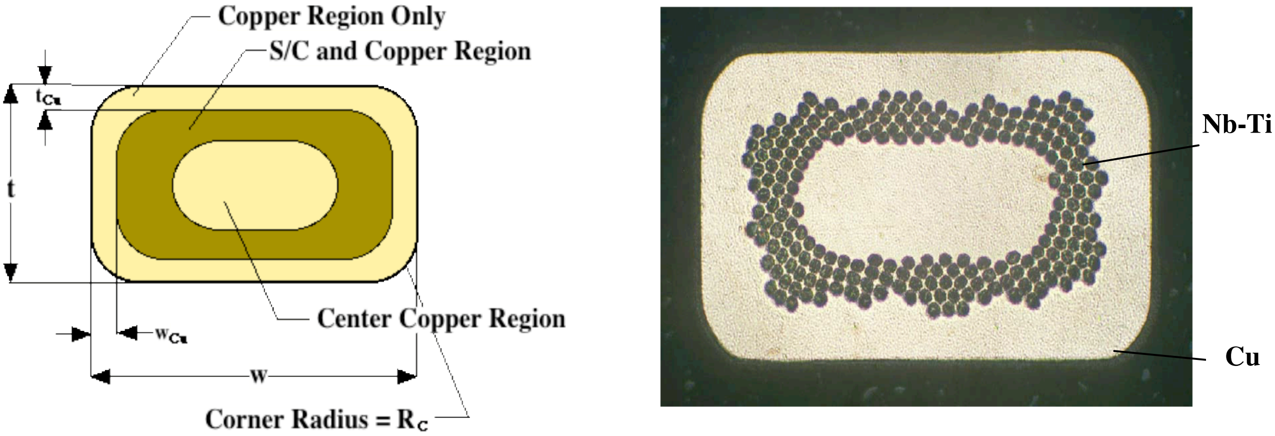

Figure 1 Coupling magnet conductor cross-section with 222 Nb-Ti filaments in a copper matrix (Ic = 760 A @5 T & 4.2 K)

The 3D view engineering structure of MICE coupling magnet is shown in Figure 2. The left side of Figure 2 is the magnet cold mass assembly with thermal shield. The right side of Figure 2 is the magnet cold mass, showing the parts of the cold mass assembly, the pulse tube coolers, the two current leads and the cold mass supports.

The basic parameters of MICE coupling magnet is listed in Table 1. The coupling magnet is the largest of the three type magnets in MICE both in terms of diameter and stored energy at design current. The temperature margin is only 0.8 K when the induction at the peak field point is 7.4T, the operating current is 210 A, and the cold mass temperature is 4.2 K. When the coupling magnet is cooled with a single small cooler, the cooling capacity margin is less than 0.2W [3]. The coupling magnet needs to vent helium gas when the AC losses and added to the static heat load. Using a second cooler permits one to charge and discharge the magnet without venting. During DC operation, the cooling margin is increased.

The primary reason for doing AC losses analysis is to determine what affect AC losses would have on the temperature distribution within the cold mass as the magnets are being charged or discharged. The affect of AC losses on coupling magnet cooling system is needed to concern also.

AC LOSSES IN MICE COUPLING MAGNET

For MICE coupling magnet, AC losses come from three sources. The first source is hysteretic AC loss, which is independent of dB/dt in the magnet superconductor per cycle. The second source is coupling loss between filaments in a multi-filament superconductor, which is proportional to dB/dt. The third source is the eddy current loss due to coupling between the superconducting coil and the mandrel and support structure, which is also proportional to dB/dt in the coil.

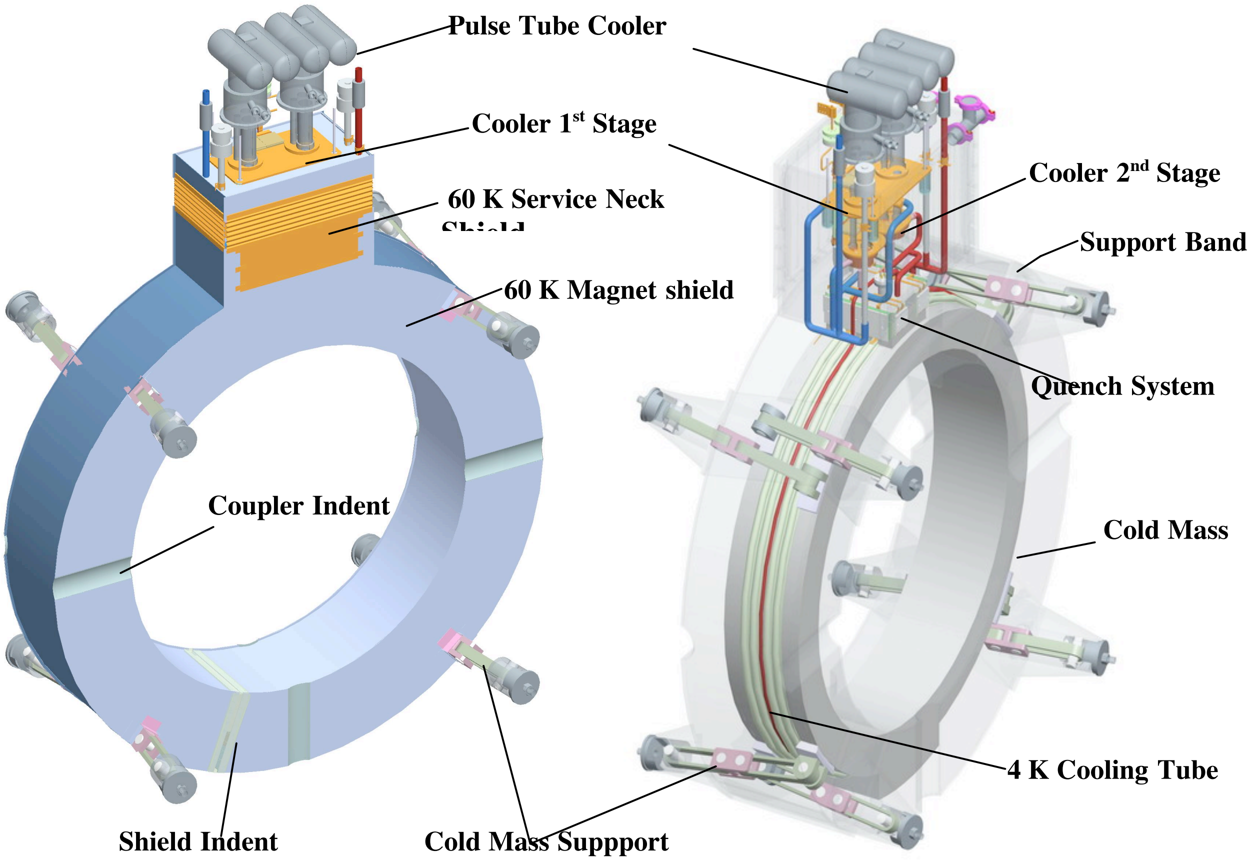

Figure 2 A 3D view of MICE coupling magnet cold Mass assembly and the 60 K thermal shield assembly

Table 1. MICE coupling magnet specifications

Parameter	Flip	Non-flip
Coil Length (mm)	285	
Coil Inner Radius (mm)	750	
Coil Thickness (mm)	102.5	
Number of Layers	96	
No. Turns per Layer	166	
Magnet Self Inductance (H)	592.5	
Magnet J (A mm-2) *	114.6	108.1
Magnet Current (A) *	210.1	198.2
Magnet Stored Energy (MJ) *	13.1	11.6
Peak Induction in Coil (T)	7.4	7.12
Coil Temperature Margin (K)	~0.8	~1.0

* Worst case design based on p = 240 MeV/c and β = 420 mm

Hysteretic AC loss in MICE coupling coil

The largest source of AC loss heating MICE coupling coil is the hysteretic AC loss in superconductor. Since the charging time for MICE coupling coil is very long (>13000 s) [4], the form of the AC losses in superconductor is primarily hysteretic losses. When the field in the conductor changes by Δ B, the hysteretic loss per volume over the coupling coil can be stated using the following expression.

$$\Delta H_c = \frac{4}{3\pi}\alpha\frac{J_c d_f}{r+1}\Delta B \tag{1}$$

with ΔH_c hysteretic loss per unit volume in coil for an induction change ΔB, α is conductor packing-factor for the coil, j_c superconductor critical current density, d_f: the superconductor filament diameter and r normal metal to superconductor ratio in the conductor. For MICE coupling coil α = 0.78, d_f =41 μm and r=4. If charged to full current, ΔB for MICE coupling coil is ~ 3 T and j_c is ~7x10^9 Am^{-2}, the average hysteretic AC loss in coupling coil is ~56 kJ m^{-3}.

Coupling loss in MICE coupling coil

Coupling AC loss is caused by the super-currents flowing between the filaments driven by voltage loops during charging and discharging process. The coupling AC loss per unit volume of superconductor can be stated using Equation 2.

$$P = \frac{2}{\mu_0}\left[\frac{dB}{dt}\right]^2\tau \tag{2}$$

with μ_0=4π x 10^{-7} Hm^{-1}, dB/dt the flux change rate in conductor and τ is coupling current time constant for the conductor, which is expressed in Equation 3.

$$\tau = \frac{\mu_0}{2\rho_e}\left[\frac{L}{2\pi}\right]^2 \tag{3}$$

with ρ_e the effective resistivity between the superconducting filaments, L the twist pitch of the filaments within conductor matrix.

For MICE coupling magnet conductor, ρ_ε = 1.2294x10^{-11} Ωm, L = 0.019 m, so coupling current time constant τ = 0.442 s, which is very short compared with charging time or discharging time. The rapid discharging time for coupling coil is 3600 s, and ΔB in coupling coil is about 3 T, so dB/dt is 0.00083 Ts^{-1} during rapid discharging. Appling Equation 2, the coupling AC loss per unit conductor volume is about 0.479 Wm^{-3}, which is two orders lower than the hysteretic AC loss for the same conductor. The coupling loss is neglected for MICE coupling coil conductor in all practical purpose.

Eddy current loss in coupling coil mandrel

The eddy current loss in mandrel is caused by eddy current induced in the mandrel by di/dt, when coupling coil closely coupling with the mandrel and support structure is charged or discharged. The mutual inductance between coupling coil and the mandrel M is 0.034 H, which is obtained using FEA method. The eddy current loss P_e can be calculated using Equation 4.

$$P_e = \frac{\left[M\frac{di}{dt}\right]^2}{R} \tag{4}$$

where R is resistance of the mandrel circuit, which can be expressed as follows;

$$R = \rho \frac{\pi D}{A} \tag{5}$$

The resistivity of the mandrel material $\rho = 1.6 \times 10^{-8}$ Ωm for 6061-T6 aluminum at 4K. D is the average diameter of coupling coil (D = 5.033 m.), and A is the cross-section area of coupling coil mandrel and support system. (A = 0.0661 m^2.) The resistance of mandrel is 3.828×10^{-6} Ω.

TEMPERATURE DISTRIBUTION IN COUPLING COIL DUE TO AC LOSSES

In order to calculate hysteretic AC loss correctly, one divides the cross-section of coupling coil into five small regions and divides the charging and rapid discharging process into four time steps. The critical current density j_c is based on the magnetic induction at the center of the block at the midpoint time of Δt. The hysteretic loss and mandrel eddy current loss calculation results for charging and rapid discharging process is summarized in Table 2 and Table 3.

The temperature distribution within the coupling magnet during charging and rapid discharging process is calculated using ANSYS. The AC losses calculated above are regarded as internal heat source. A heat flux of 0.2 Wm^{-2} as radiation is applied to the cold mass surface area of coupling coil. A heat flow of 0.039 W is an added heat leak due to each cold mass support is applied to support attachment area. The cooling tubes are at 4.27 K. The ΔT between the highest temperature point within cold mass and the cool tube during charging and rapid discharging process is listed in Table 2 and Table 3 during charging and rapid discharging process.

Table 2. AC losses and temperature drop with time during charging process

Time (s)	Hysteretic Loss (W)	Mandrel Loss(W)	AC loss (W)	ΔT(K)
1733	1.63	0.05	1.698	0.225
5198	0.93	0.05	1.001	0.14
8663	0.61	0.05	0.678	0.10
12127	0.46	0.05	0.528	0.082

Table 3. AC losses and temperature drop with time during rapid discharging process

Time (s)	Hysteretic Loss (W)	Mandrel Loss(W)	AC loss (W)	ΔT(K)
450	1.78	1.02	2.80	0.221
1350	2.37	1.02	3.39	0.292
2250	3.62	1.02	4.64	0.438
3150	6.32	1.02	7.34	0.739

From the results above, it can be concluded that the coupling coil can be charged at the full voltage of the power supply, if 5~6 liters liquid helium boils away during charging process. The coupling coil can be rapidly discharged within an hour using a varistor [5], and about 8 liters liquid helium will boil away during rapid discharging process. The sensible heat from the boiled helium can be used to keep the top of the HTS leads cold enough to prevent them from going normal.

CONCLUSION

The MICE coupling magnet will be fabricated using standard MRI magnet conductor. The magnet has a maximum stored energy of 13.1 MJ and a full operating current 210.1 A. The hysteretic loss is the largest type of AC loss during charging and discharging process. The eddy current loss in mandrel plays an important role during rapid discharging process. The values of AC losses and temperature distribution within the cold mass indicate that MICE coupling magnet can be charged and rapidly discharged safely if several liters of liquid helium boil away. The analysis result is to be further confirmed by the experiment of the prototype solenoid for MICE coupling magnet, which will be designed, fabricated and tested at ICST.

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